DOCUMENT RESUME

ED 098 019 SE 014 848

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TITLE	The Role of Explanation and Prediction in Determining Science Curriculum Content.
INSTITUTION	Memorial Univ., St. John's (Newfoundland).
PUB DATE	[72]
NOTE	14p.
EDRS PRICE	MF-$0.75 HC-$1.50 PLUS POSTAGE
DESCRIPTORS	College Science; Curriculum; *Curriculum Development; *Prediction; *Science Curriculum; *Science Education; *Secondary School Science

ABSTRACT

Presented is a discussion of the role of explanation and prediction in determining science curriculum content. It is the author's contention that many of the concepts currently presented in high school and college science courses are based on assumptions long rejected as false by scientists because curriculum designers have failed to examine carefully the difference between explanation and prediction as bases for acceptable scientific theories. It is suggested that curriculum be developed which is based on a study by analogy of the more familiar and easily understood examples of explanation and prediction in science, thereby allowing students to look on explanations as useful but tentative models for examining the universe. (Author/PEB)

THE ROLL OF EXPLANATION AND PREDICTION IN DETERMINING SCIENCE CURRICULUM CONTENT

by

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THE ROLE OF EXPLANATION AND PREDICTION IN DETERMINING SCIENCE CURRICULUM CONTENT

ABSTRACT

Many of the concepts currently presented in high school and college science courses are based on assumptions which have long been rejected as false by scientists. This paradox exists, in part, because curriculum designers have failed to examine carefully the difference between explanation and prediction as bases for acceptable scientific theories. This failure is rooted in a misinterpretation of what is known as the Correspondence Principle, the principle which holds that any new theory in science must reduce to the old well-established theory to which it corresponds when the new theory is applied to the circumstances for which the less general theory is known to hold. While this is certainly true with respect to predictions, i.e. any new theory must be at least as good as the old theory in accounting for observed phenomena, it is often not the case with respect to explanations.

New theories in science often present entirely different ways of viewing and explaining nature, even though under corresponding circumstances their predictions are essentially the same as those of the theories they replace.

The failure to take account of these differences raise serious problems in future science curriculum design. While it may seem appropriate to emphasize the teaching of new theories in place of older ones, it must be recognized that many of the new theories of today will be the old theories of tomorrow. Does it make sense to constantly revise our curriculum simply to keep up with current theories which have not yet been disproved? The situation is made more complex by the fact that many of our new, broader theories are more difficult to understand and to teach than are the theories they replace. On the other hand how long can we continue to teach theories which work in a predictive sense but are based on false explanations?

One possible solution is to reject explanation altogether as a basis for scientific theories and to rely solely on the criteria of accurate prediction. Some philosophers of science argue for this position, but most are

unwilling to accept such an approach. A more useful approach is to develop a curriculum based on a study by analogy of the more familiar and easily understood examples of explanation and prediction in science, thereby allowing students to look upon explanations as useful but tentative models for examining the universe.

THE ROLE OF EXPLANATION AND PREDICTION IN DETERMINING SCIENCE CURRICULUM CONTENT

Richard M. Reis

INTRODUCTION

Much of the content of our present high school and college science programs is based on outdated scientific theories which were popular at the end of the 19th century. Our science curriculum has failed to consider many of the fundamentally new theories which have emerged during the past 75 years. These new theories provide not only more accurate predictions but also completely new explanations which have actually replaced explanations of the past. The situation in which we continue to teach concepts based upon assumptions which have long ago been rejected as false by scientists is due to the failure of curriculum designers to consider carefully the distinction between explanation and prediction in science.

This paper will examine some of these important distinctions, discuss the implications they have for science curriculum design, and conclude with a look at possible new approaches required in teaching the nature of science.

EXPLANATION vs PREDITION

The ability to predict future observations and experimental results is considered by many scientists to be the essential characteristic of a scientific theory. Yet the history of science is replete with examples of predictions which are based upon very poorly constructed theories. Conversely, there are numerous examples of elaborate theories or explanations which have yielded no predictions whatsoever.

The Babylonians (600-400 B.C.) were expert at making accurate predictions without the use of an explanatory base or theory. While they were masters at calculating the times and dates of astronomical events, such as lunar eclipses, new moons, and positions of the major planets, their writings reveal no theories or even thoughts about the heavens. [1]

On the other hand, the Ionians, who lived and practiced astronomy at about the same time, developed elaborate theories and interpretations from which it was impossible to make predictions. Their theories used homely analogies to explain the heavens. The universe was compared to a tube full of fire with holes in it through which stars were visible. There is little evidence that they attempted to predict such things as eclipses or the positions of planets; and it is doubtful, considering their theories, whether such predictions would have been successful.

While the Babylonians were successful in certain predictions, their failure to develop explanations placed them in the pre-science era. Toulman argues that all science must have at least a minimum theoretical base, even if this base is shown to rest on false assumptions and is subsequently rejected. [2] Kuhn has pointed out that even unsuccessful theories can serve the very useful purpose of focusing the attention of a scientific community on a particular problem. [3]

Of course the most desirable situation would be a combination of explanation and prediction, or theories which yield reasonably good predictions. This is essentially the pattern that has developed in most mature sciences over the past few centuries. However, we must realize that many theories which are good predictors today may, upon further examination, turn out to be based on false assumptions and will, in turn, be replaced by entirely new explanations.

Good theories yield predictions which are in turn tested by experimentation. Continued experimentation may reveal that the original theory or model is unable to account for new observations. Over a period of time this will lead to a modification of the original theory or in some situations to its complete demise and replacement by an entirely different theory.

A familiar example of this was the change from the Ptolemaic or Earth-centered model to the Copernican or Sun-centered model of the solar system. The Ptolemaic model is a reasonably good predictor of the positions of the sun, moon and planets and even today it can be used with some success in earth-based navigation. However, the failure of these predictions to conform to the much more accurate observations of the 16th century led to the eventual rejection of the Ptolemaic model and its replacement by the Copernican model. It was this failure to predict at a very high degree of accuracy that provided the impetus for the development of an alternate concept. Yet while both models are able to predict the positions of the sun, moon and planets (although at different levels of accuracy) it is important to note that the models themselves represent entirely different and mutually exclusive ways of describing the motion of the planets. Each represents an entirely differe way of viewing the structure of the solar system even though their predictions merge within a particular range of observations.

Now which model should we teach our students? In this situation the answer seems clear enough. While we may actually teach about both of them, since the two models are mutually exclusive, one at least must be rejected as incorrect. While we cannot know for certain if a theory is true in science we can now when it is false, and in this case we do not teach the Ptolemaic model as a true model of the solar system.

Yet in other areas of science we continue to teach concepts based upon models and theories which have long ago been rejected by scientists. We are in the seemingly untenable position of teaching incorrect concepts to students who will probably never take another formal course in science.

Our science curriculum is, for the most part, devoid of the new concepts and theories of the 20th century which have replaced the classical theories of the previous century and have so revolutionized our view of the universe.

The main reason for continuing to teach theories based on false assumptions is our lack of understanding about the differences between explanation and prediction. This lack of understanding results from a misinterpretation of what is known as the Correspondence Principle.

This principle, first applied in a limited way by Niels Bohr to the theory of atomic structure, has since been used in a much broader sense to cover other theories in physics, chemistry and biology.

The principle as stated by Bohr in 19‾3 is:

> "that ... in the limit of high quantum numbers the predictions of quantum theory agree with those of classical physics." [4]

Presented in this limited way its meaning is fairly clear. The emphasis is on the word predictions. Bohr is saying that for the macroscopic world (high quantum numbers) the predictions of quantum mechanics and classical physics agree. The predictions of any new theory must be at least as good as those of the older well-established theory it replaces.

If, on the other hand, we adopt the broader statement of the Correspondence Principle taken from a popular elementary science text, serious misinterpretations can result.

> "We know in advance that any new theory in physics (science) -- whatever its character or details -- must reduce to the well-established classical theory to which it corresponds when the new theory is applied to the circumstances for which the less general theory is known to hold." [5]

Stated in this way we are led to believe that new broader theories or explanations actually reduce to, or become, older theories when applied to circumstances for which the older less general theories are known to hold -- a situation which rarely is true in science. It would mean that the Copernican model of the solar system reduced to or became the Ptolemaic model when applied to the circumstances of less accurate observations. This is of course absurd. While their predictions correspond closely under certain circumstances, the models or theories themselves are quite dissimilar ways of viewing the universe. New theories in science often present entirely different ways of viewing and explaining nature, even though under corresponding circumstances their predictions are essentially the same as those of the theories they replace.

Science teachers do not seem to have difficulty in distinguishing between prediction and explanation in simple models of the solar system, but as soon as they move to somewhat more sophisticated concepts in the science curriculum, these distinctions are glossed over.

When the engineer assumes that the acceleration due to gravity is the same at the top and at the bottom of a tall building he is making an assumption that is completely reasonable in a predictive sense. The difference between a constant acceleration and one calculated from the inverse square law is a difference of one part in 10^{23}! Yet the two assumptions, one of a constant acceleration and the other of an acceleration that decreases inversely as the square of the distance measured from the center of the earth, are fundamentally different ways of describing nature. In an explanatory sense Newton's Inverse Square Law does not reduce to a case of constant acceleration for small changes in distance.

A more relevant example would be a comparison of the Newtonian and Einsteinian theories of dynamics. The predictions of Newtonian dynamics have been quite good when dealing with natural speeds one would observe at or near the surface of the earth. But for objects attaining speeds more than ten percent of the speed of light (more than 20,000 mi/sec) the predictions of Newtonian dynamics become increasingly inaccurate. The predictions of Einsteinian dynamics, on the other hand, conform closely to observations of objects going up to and including 99.9% of the speed of light. Of course Einsteinian theory also predicts with great accuracy observations below 10% of the speed of light, that is, in circumstances where Newtonian dynamics was quite successful. Therefore, Einstein's theory is a much broader, more encompassing theory. Einstein's theory will predict all that Newton's will and much more. Yet the two theories themselves are quite different. To see how this is possible, consider as a specific illustration the assumptions that each make about the mass of an object.

Newtonian dynamics assumes that the mass of an object is independent of its speed. This can be expressed in a simple way by the equation,

$$m_v = m_o$$

where m_v is the mass of an object moving at speed v, and m_o is the mass of this same object at rest.

Einsteinian dynamics, on the other hand, assumes that the mass of an object is a function of its speed, increasing as the speed of the object increases. This is expressed by the equation,

$$m_v = \frac{m_o}{\sqrt{1 - v^2/c^2}}$$

where v is the speed of the object and c is the speed of light. By substituting into this equation one can see that for speeds much in excess of 0.1c the mass of the object becomes significantly greater than its rest mass. For speeds less than 0.1c the mass of the object is very close to its rest mass. The difference is so small that it can be detected only by the most sophisticated instruments.

But this does not mean that Einstein's theory of dynamics reduces to Newton's theory in the realm of low velocities. We are not talking here about a minor difference in the sixth or seventh decimal place, but rather about entirely different theories. Constant mass and mass which is dependent upon velocity are completely different concepts. Newtonian and Einsteinian models represent entirely different ways of describing nature, even in the area where their predictions overlap. We cannot accept both of these theories for the same reason that we cannot accept both the Ptolemaic and the Copernican models. Or as Kuhn has said, "In order to accept Einstein we must reject Newton."[6] While we cannot prove Einstein right, we can and have proven Newton wrong. We cannot teach Einsteinian theory only for objects attaining speeds greater than 20,000 mi/sec. Yet our curriculum places major emphasis on Newtonian mechanics while barely mentioning the work of Einstein.

A similar situation exists between quantum mechanics and classical physics although there are special features of the quantum mechanical model that require special attention.

The Uncertainty Principle places a limit on the predictability of the position and velocity of small particles. Thus it may appear that the quantum mechanical theory is a less accurate predictor than the classical theory it replaces. Upon closer examination this is shown not to be the case. It is important to distinguish between exact predictions and accurate predictions. The predictions of quantum mechanics are more accurate than those of classical physics although what they predict is less exact. Classical theory predicts that one can describe with certainty the position and velocity of a particle. This prediction is inaccurate or wrong. Quantum theory on the other hand predicts that descriptions about the position and velocity of a particle will be uncertain or inexact to some extent. In this sense quantum mechanics is a more accurate predictor than the classical theory it replaces.

Again, in ways similar to the situation of Newton and Einstein, our physics curriculum places major emphasis on the simplified Bohr model of the atom with virtually no mention of the Wave Equation or the Uncertainty Principle.

Likewise, in other areas such as cosmology, geophysics, and genetics there have been significant advances which have forced scientists to reject previous theories, yet we continue to teach the rejected theories with little or no mention of those theories which supersede them.

At the very most, current theories are treated as supplementary topics which one "gets around to" if there is time at the end of the course. Certainly they are not regarded as central conceptual schemes on which to build modern science curriculum.

IMPLICATIONS FOR SCIENCE CURRICULUM DESIGN

How then do we solve this problem in future science curriculum design? Must we discard most of our elementary science textbooks and replace them with ones that give only treatments of contemporary theories in physics, chemistry, and biology? This would be a massive undertaking involving much time, effort, and expense. There are several arguments against taking such a radical step.

One is that many of these older concepts continue to work in a predictive sense when applied to a wide range of phenomena. One could argue at length with an engineer about the incorrectness of the assumptions underlying Newtonian mechanics, yet the fact remains that this relatively simple model allows the engineer to construct very real buildings, bridges, airplanes and automobiles. He rarely needs to consider the more sophisticated and difficult concepts of relativity. For him the test of the value of a model is whether or not it can be used to produce a workable solution to a practical problem.

The scientists, and by implication the science student, is interested in much more. He is interested in explanation as well as prediction. It is this striving for explanation or understanding that gives meaning to his work. It is the qualitative difference between the Ionians and the Babylonians.

Certainly we must teach the engineer about Newton's Laws and the navigator about the Ptolemaic model, but in so doing we must emphasize that we are talking about something that is acceptable only in the predictive sense. We must also present a much broader picture which examines the various criteria determining the validity of a theory or a model and makes clear the important role of explanation. We cannot continue to teach incorrectly based concepts solely on the grounds that they are reasonably good predictors.

A second argument for not over emphasizing contemporary theories in an introductory science course is a lack of time. There is not enough time, it is argued, to teach both Einsteinian dynamics and Newtonian dynamics; or the Bohr model of the atom and the quantum mechanical model. This problem of time is a real one. And the fact remains that one or two semesters is probably all the time we will ever have with a group of students. Our introductory science course is likely to be the last science course these students will ever take, and it appears from this argument that we have enough time to teach incorrect explanations, but not enough time to teach more acceptable explanations.

A third argument against rushing to teach only contemporary theories is more important from a pedagogical point of view. It presents scientists and science educators with a true dilemma. The argument is that many of the contemporary theories in science are so difficult that most students and many teachers could not understand them. This is sometimes true even for scientists. As Wolfgang Pauli observed in the early 1920's:

> "At the moment physics is again terribly confused. In any case, it is too difficult for me, and I wish I had been a movie comedian or something of the sort and had never heard of physics." [7]

To present, in an honest way, the concepts of relativity and quantum mechanics requires a depth of understanding few physics majors received in four years of university work. The problem of presenting this information in one year to terminal science students is obvious enough.

Perhaps this is the real reason we have found time to teach both the Ptolemaic and Copernican model but not the time to teach the theories of both Newton and Einstein. The former are easily understood and within the realm of everyday experiences. This is not the case with the latter (quantum mechanics and relativity). Does this situation mean that we have actually reached a point in the development of science where current theories and paradigms are incomprehensible to the vast majority of our population? If this is so, then science will continue to lose touch with the very people who benefit from it and who are asked to support it.

In addition to the above arguments, there is a more fundamental reason why we should not discard all old theories and teach only the latest advances.

This reason is rooted in the very nature of science itself. We know from a study of history that, at least in the explanatory sense, the new theories of today will most likely be the old theories of tomorrow. While we can be reasonably sure that present theories will continue to predict with a certain degree of accuracy, we cannot be as sure that their explanations will remain valid. When one considers the advances science has made in the past century it is reasonable to suppose that, within our students' lifetime, a number of today's theories will become outdated.

In placing excessive emphasis on what is current in science we enter a futile race to keep one step ahead of the latest advance. This will not help our students interpret science 20 or 30 years after they have left school. If a major goal of science education is to produce autonomous learners, then we must give students something that has survival value. Something that will allow them to adapt to the accelerating changes in science that will take place in the decades to come. This something involves more than an understanding of basic concepts and principles. It involves an understanding of how science itself progresses. It involves the development of a model that brings out clearly the distinctions and at the same time points out the interrelationship between explanation and prediction. We should use a model which allows students to incorporate new advances in science into a stable structure. They should realize that explanations serve as useful but tentative models around which further predictions and advances can be made and that these explanations are not final truths in themselves.

FUTURE POSSIBILITIES

This paper then is an argument for a curriculum the central focus of which should be to examine the nature of science, the scientific enterprise and the characteristics of scientists. To accomplish these ends in high school and liberal arts college courses students need more than standard treatments of the history and philosophy of science -- treatments which tend to be too abstract and removed from their everyday experiences. New, imaginative approaches using case histories, visits with scientists, and research projects are steps in the right direction.

In addition, more attention needs to be given to the use of analogies and simulation games in the classroom. Analogies serve as learning tools which connect what the student already knows with what he is presently trying to learn. Thus the analogy between the Ptolemaic and Copernican models can be used to illustrate the form of present and future changes in scientific theories.

Simulation games can provide the necessary vehicle to tie analogies together, to provide motivation, and to connect analogies with the students' everyday experiences. Pioneering work has been done in this respect in the teaching of the social sciences economics and education, but very little has been attempted with natural science curricula.

By providing a framework which makes clear the function of explanation and prediction in science we will be helping students to understand more clearly the prospects and limitations of science in the decades to come.

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